



## Extreme Design Loads Calibration of Offshore Wind Turbine Blades through Real Time Measurements

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*Publication date:*  
2014

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### *Citation (APA):*

Natarajan, A., Vesth, A., & Lamata, R. R. (2014). *Extreme Design Loads Calibration of Offshore Wind Turbine Blades through Real Time Measurements*. Poster session presented at European Wind Energy Conference & Exhibition 2014, Barcelona, Spain.

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## Abstract

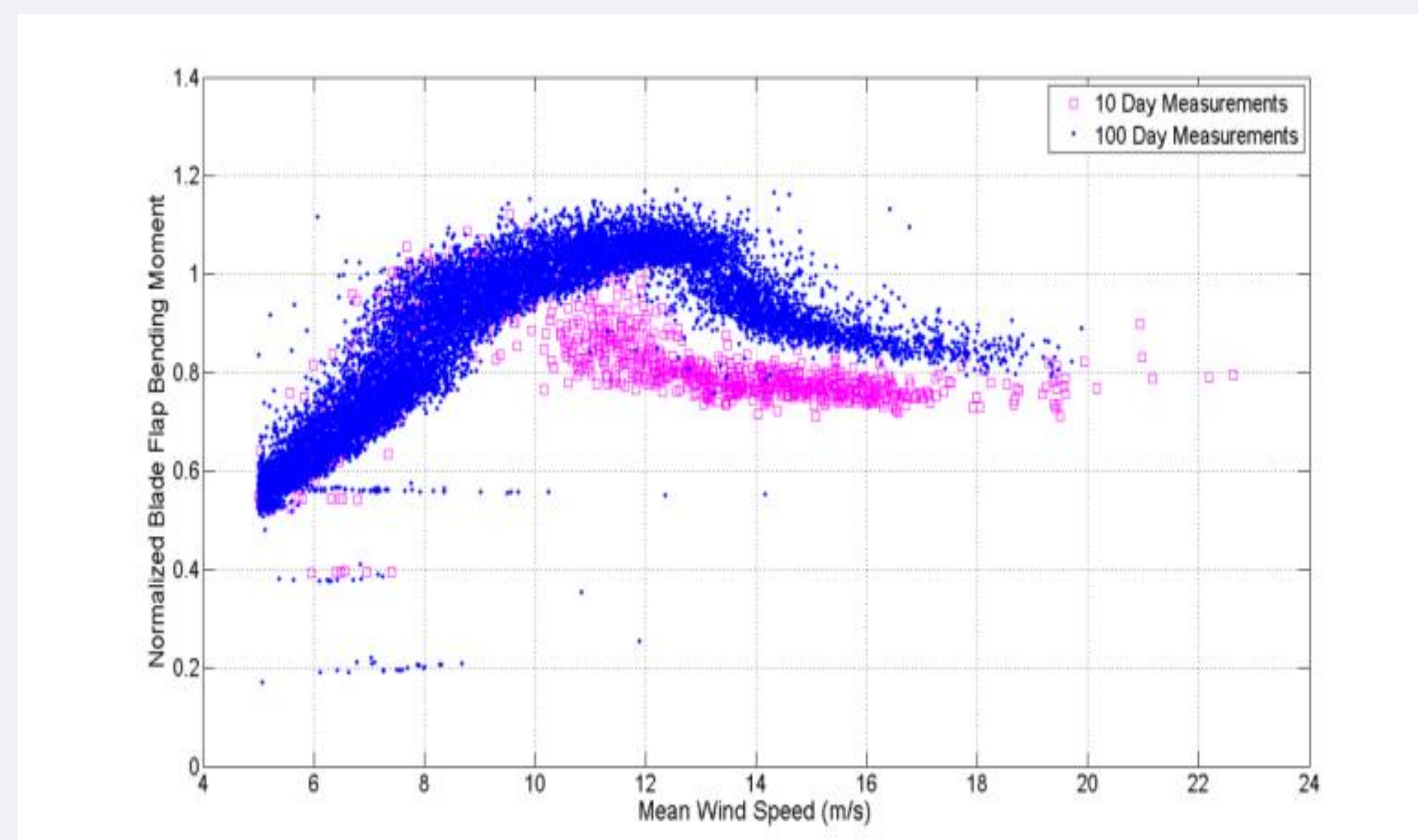
Blade root flap and edge moments are measured on the blades of a 3.6MW offshore wind turbine [1] in normal operation. Ten minute maxima of the measurements are sampled to determine the extreme blade root flap moment, edge moment and resultant moment over six month duration.

A random subset of the measurements over a week is taken as input to stochastic load extrapolation whereby the one year extrapolated design extreme is obtained, which are then compared with the maximum extremes obtained from direct measurements over a six month period to validate the magnification in the load levels for the blade root flap moment, edge moment obtained by extrapolation.

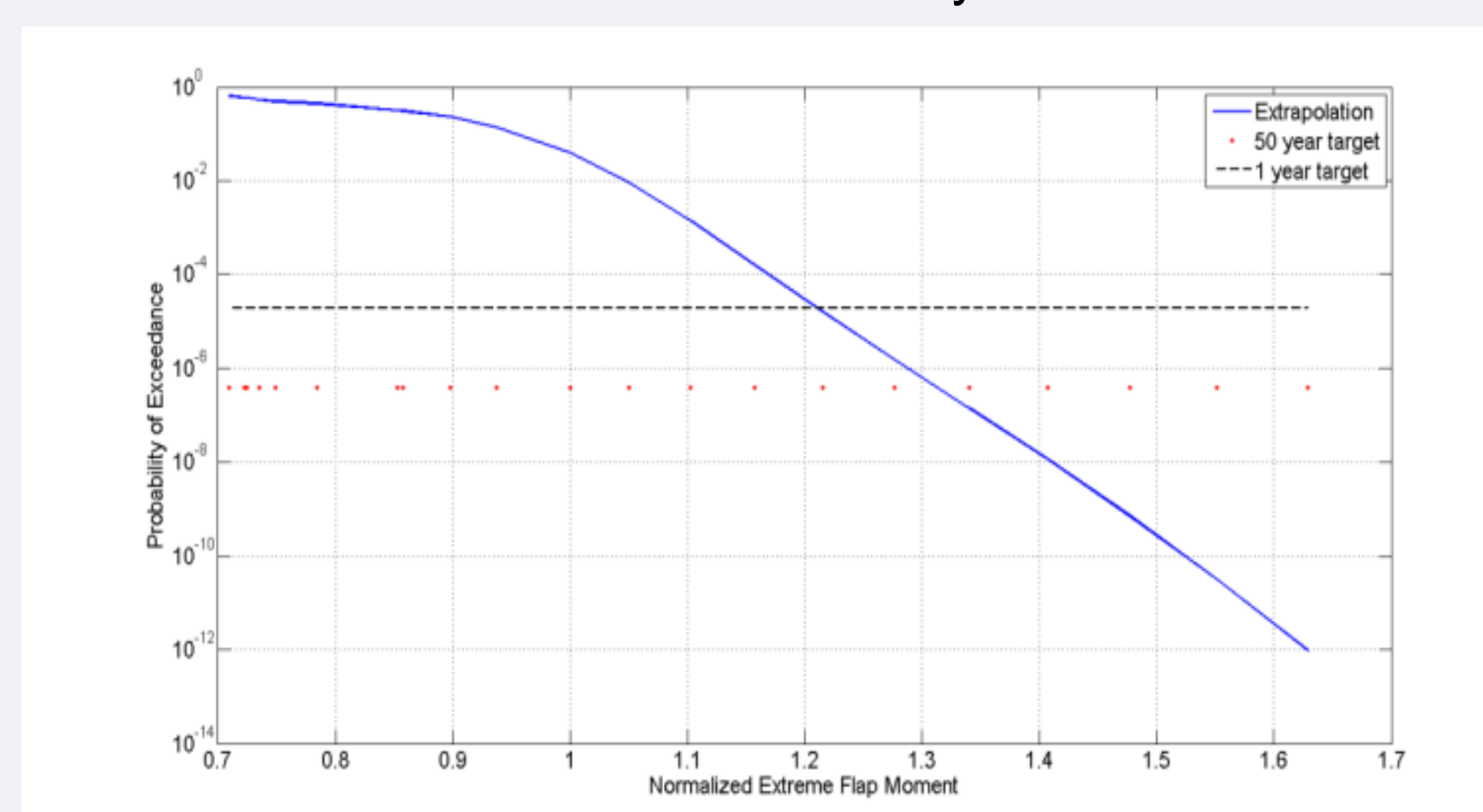
The validation yields valuable information on prescribing the slope of the local extrapolation curve at each mean wind speed. As an alternative to determining the contemporaneous loads for each primary extrapolated load, the blade root resultant moment is extrapolated. This is found to possess smaller scaling factors in measurements over six months as compared to both the flap and edge moments, indicating that the contemporaneous load component of an extrapolated load should possess much smaller magnitude than its maxima.

## Measured Loads

Measured blade root Max flap moments over 100 days as compared with maximum flap moments over 10 days normalized with a random one day maximum



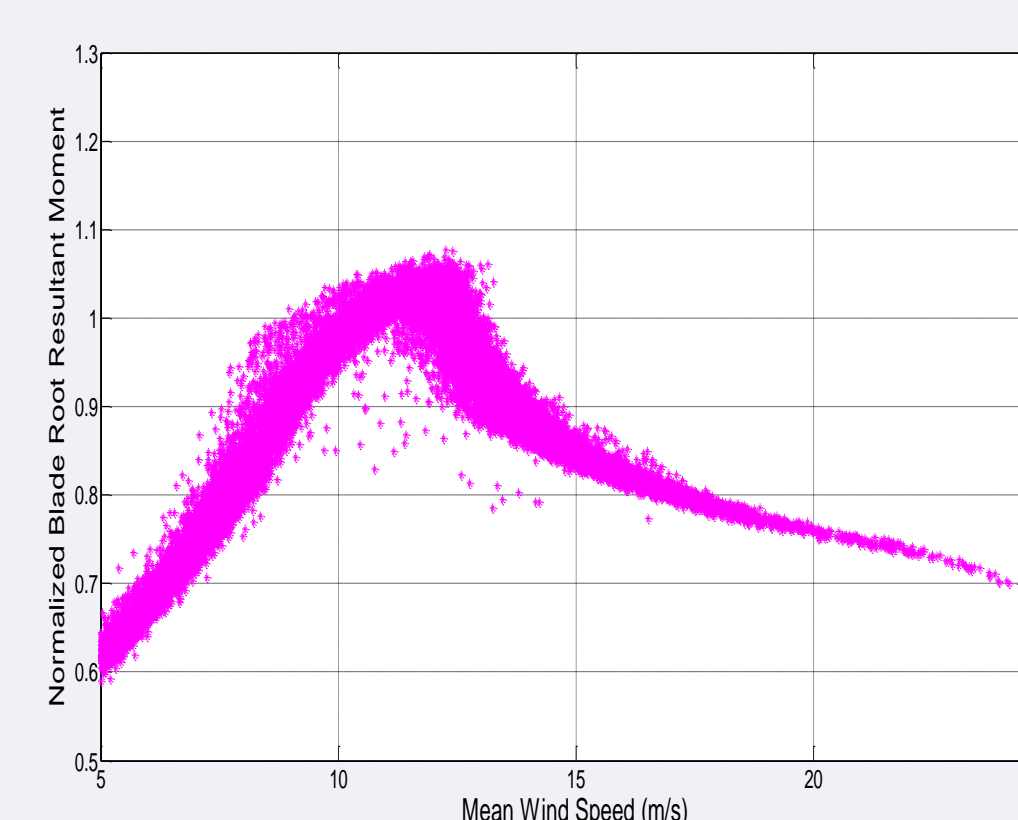
Extrapolated Maximum Flap Moments normalized with a one day maximum



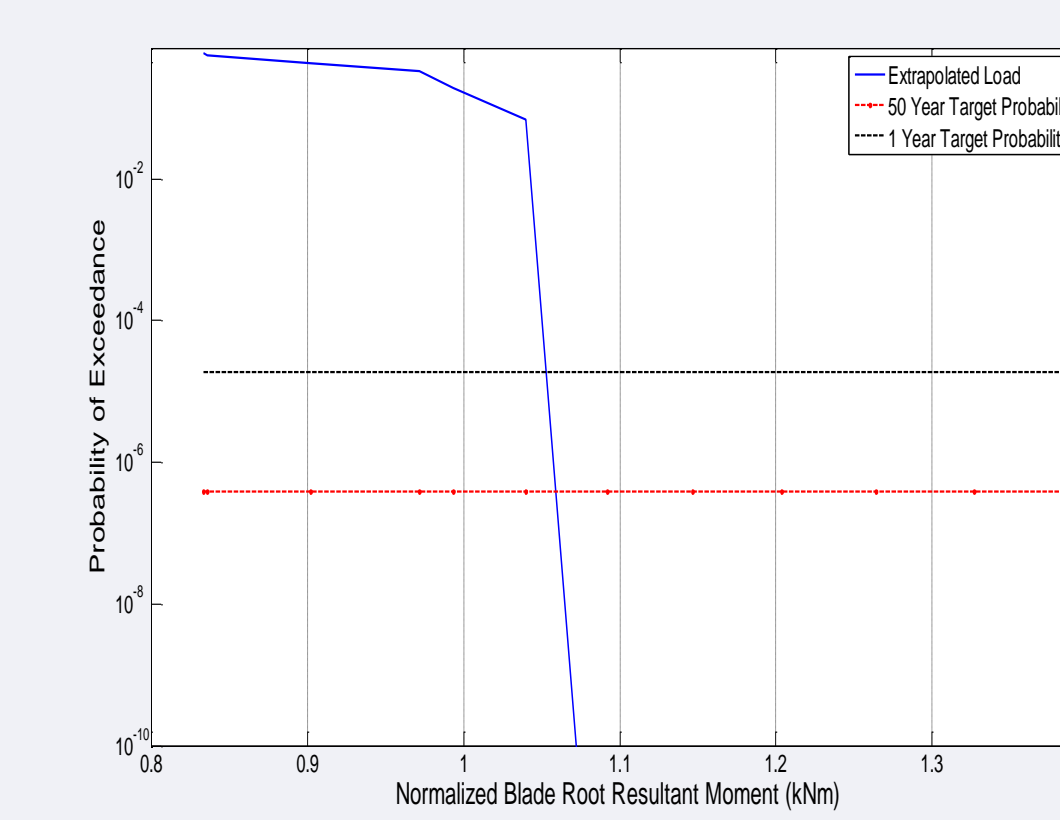
## Results

All extrapolations used 30 ten minute measured maxima at each mean wind speed and normalized by a random one day maximum load value.

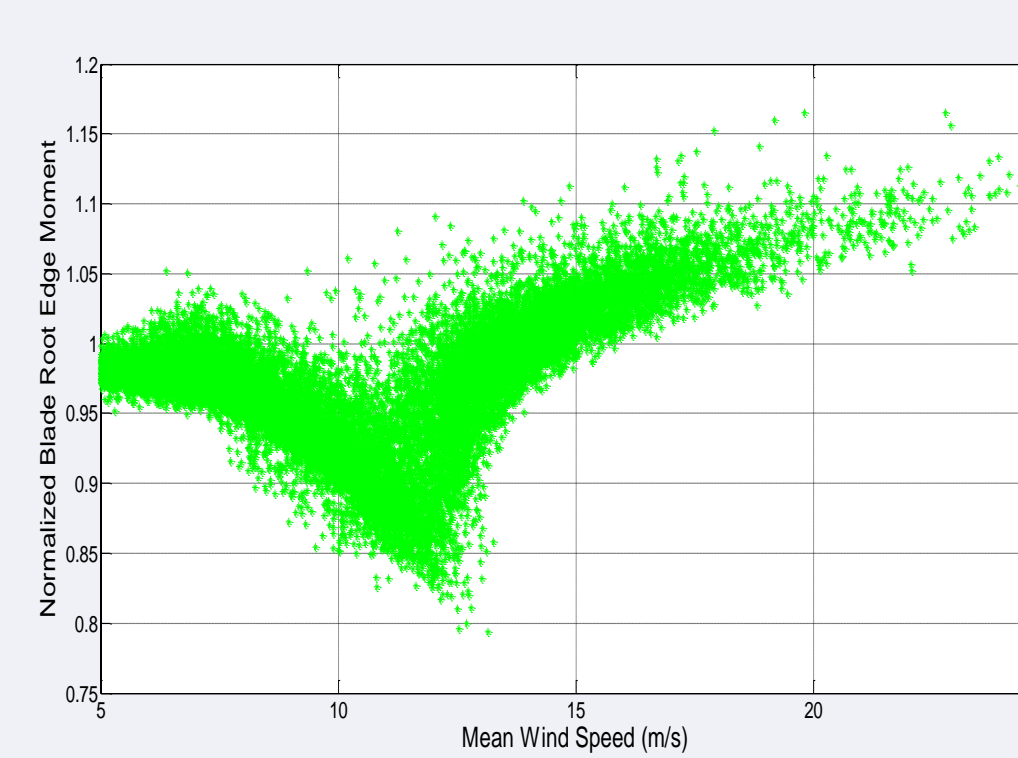
### Measured Blade Root Resultant Moment Maxima



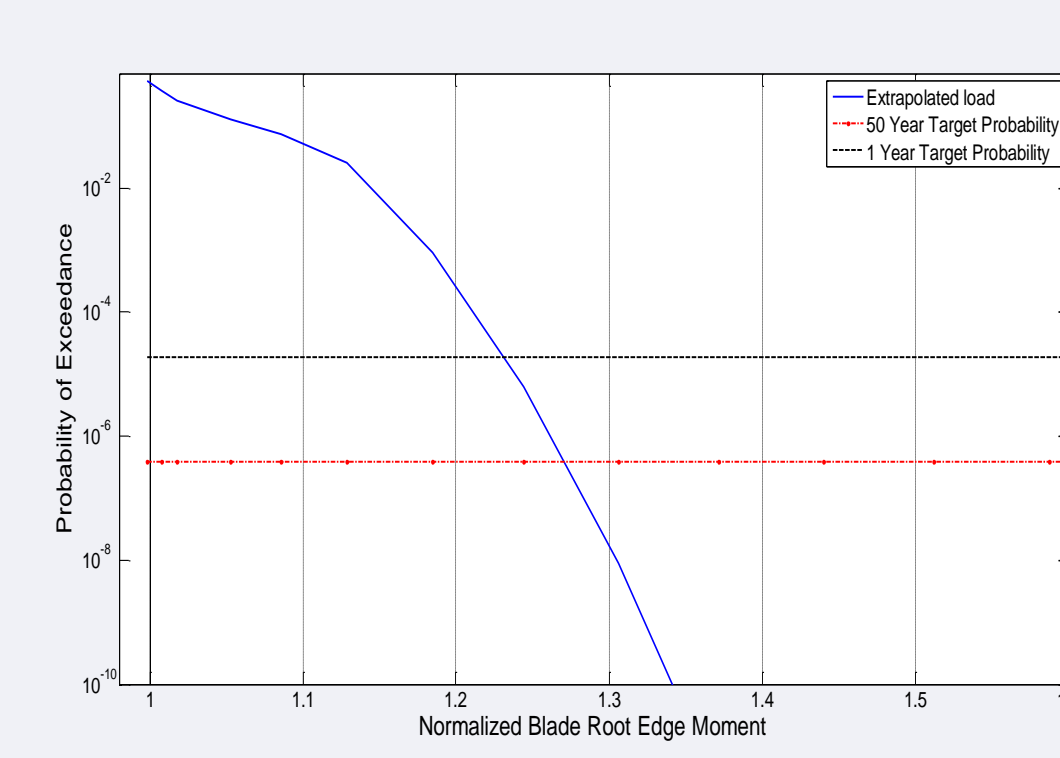
### Extrapolated Blade Root Resultant Moment



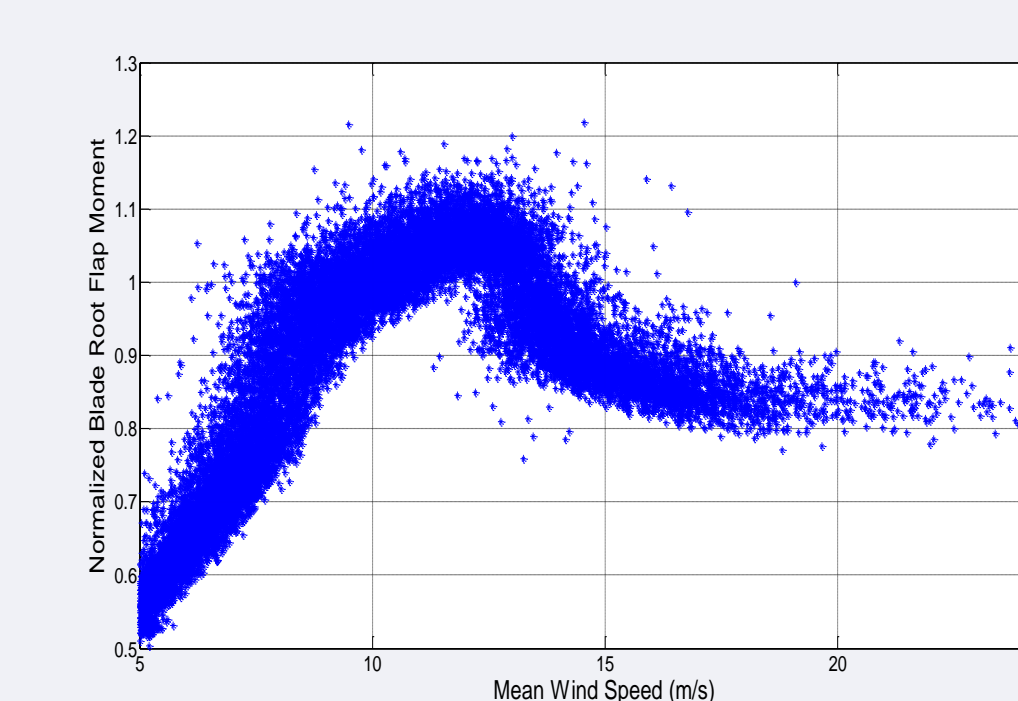
### Measured Blade Root Edge Moment Maxima



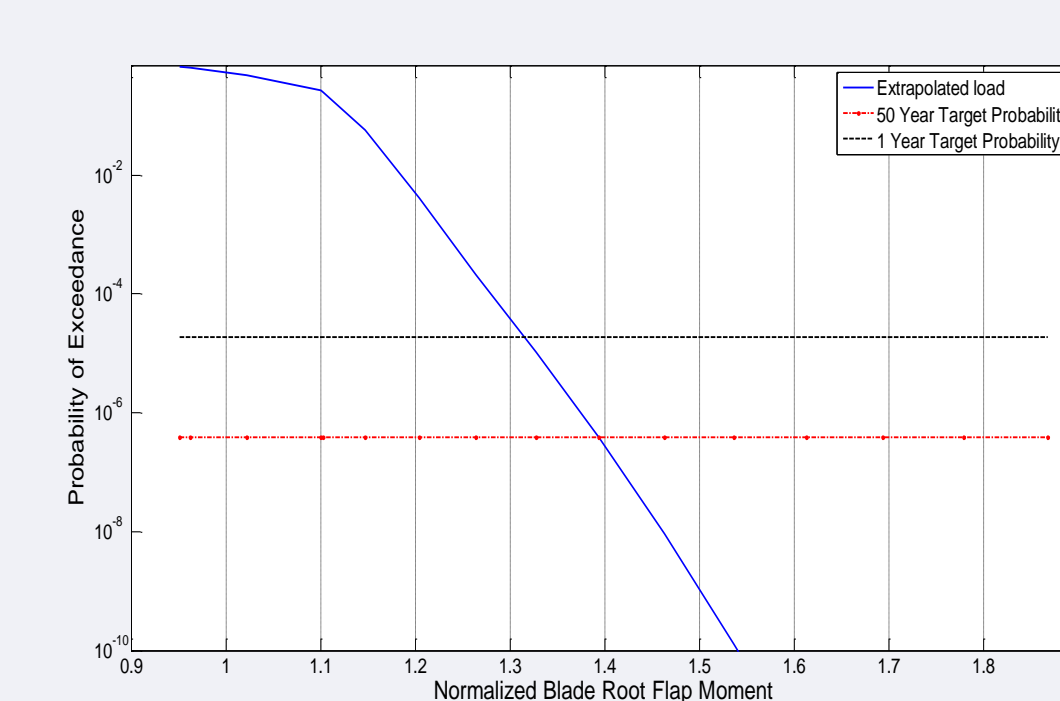
### Extrapolated Blade Root Edge Moment



### Measured Blade Root Flap Moment Maxima



### Extrapolated Blade Root Flap Moment



## Extreme Load Extrapolation

The IEC 61400- 3 [2] requires that the extreme loads over the rotor of an offshore wind turbine in normal operation as determined using limited computer simulations be extrapolated to a 50 year return period.

- This is done by applying a stochastic distribution to the tail of the extreme loads data - A Gumbel distribution with a distorted quadratic exponent as described in [3]. The long term probability of exceedance  $P$  that the extreme load  $F_e$  exceeds a given level  $F$  is thereby given by Eq. (1) wherein the probability of the mean wind speed has been assumed to be Rayleigh distributed.
- Only measured blade root extremes over different random ten minute intervals are used to fit the distribution functions. 30 random ten minute measured extremes are used at each mean wind speed.
- The magnification in the 1-year extrapolated extreme load over a 1day extreme is compared with the magnification obtained in measurements over a 6 month operational period.
- The blade root flap, edge and resultant moment are extrapolated.
- The key objective is to determine a validated load extrapolation method that bounds the magnification of the extrapolated extreme load value to the maximum in the measurement period for different load components.
- As required for blade design, the contemporaneous edge moments for extreme extrapolated flap moments or contemporaneous flap moments for extreme extrapolated edge moments are also determined.

$$P(F_e > F) = \sum_{i=1}^{outout} \left\{ \left( e^{-\pi \frac{(v_i - \bar{v})^2}{2\sigma^2}} - e^{-\pi \frac{(v_i + \Delta v_i)^2}{2\sigma^2}} \right) (1 - (e^{-e^{-(a(v_i)F^2 + b(v_i)F + c(v_i))}}))^{\bar{v}_i} \right\} \quad (1)$$

## Constraints on Load Extrapolation

- The Gumbel distribution with the quadratic exponent ( $G(F)$ ) is not a conventional distribution function and is valid only in the tail region of a stochastic process [4].

$$G(F) = e^{-e^{-(a(v_i)F^2 + b(v_i)F + c(v_i))}}$$

- To ensure that the Gumbel cumulative distribution asymptotically approaches unity, coefficients of the exponent are constrained as:  $a, c > 0$  &  $b < 0$
- The necessary subset of sampled loads required to establish a robust fit is determined based on the condition that the derivative of the exponent is maximum over the sampled data points as compared to any other data sample.

$$\left( \frac{d\tau}{dF} \right)_{i=1..m} > \left( \frac{d\tau}{dF} \right)_{i=1..n \neq m} \quad \forall i 1..n$$

$$\tau = a(v_i)F^2 + b(v_i)F + c(v_i)$$

## Contemporaneous Loads

- For blade ultimate strength design, the extrapolated primary load must be combined with simultaneously occurring load components.
- However information regarding the coincident loads corresponding to an extrapolated primary load is lost. Approximate methods of identifying a coincident load from the simulated load set used for load extrapolation have been explained in the IEC 61400-1 Ed.3[5].
- In this work, a different approach is used of extrapolating the blade root resultant moment, which is seen to possess much lower extrapolation magnification factors compared to the flap or edge moments.
- The extrapolated resultant moment is used in blade design by orienting its direction that produces the largest strain at the corresponding blade section

## Conclusions

The extrapolation method was calibrated based on measured maxima and the resulting one year extrapolated load level showed acceptable and similar magnitudes as compared with the measured extreme loads for all three blade root load components, the flap moment, edge moment and resultant moment.

- Based on measurements, the blade resultant moment displayed consistent maxima that were bounded and stayed below 10% magnification when comparing 6 month extremes with a 1 day extreme as opposed to flap and edge moments, which showed about 25% magnification.
- If the blade ultimate strain levels are computed based on flap and edge components only, then it is robust to extrapolate the resultant moment and resultant forces on a blade section than to determine contemporaneous loads to primary extrapolated loads.

- The extrapolated resultant moment or force can be set in the direction that maximizes the bending strains at that section, during blade design.

## References

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## Acknowledgments

The work presented is a part of the Danish EUDP project titled, "Offshore wind turbine reliability through complete loads measurements", project no. 64010-0123. The financial support is greatly appreciated.